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Theodolite-borne vector Overhauser magnetometer: DIMOVER

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This report covers results of the long-term research directed at developing an absolute vector proton magnetometer based on the switching of bias magnetic fields. The distinctive feature is the attempt of the installation of a miniature Overhauser sensor and optimized Garret solenoid directly on the telescope of the theodolite. Thus this design (Declination Inclination Modulus Overhauser magnetometer: DIMOVER) will complement the universally recognised DIflux absolute device by adding full vector measurement capability. Preliminary designs, which also can be interesting to the experts in vector proton magnetometers, are presented.
Key words: Overhauser magnetometer, magnetic observatory instrumentation, DIflux, magnetic declination, magnetic inclination.

1. Brief Review of Modern Proton Component Magnetometers

The vector proton magnetometers were developed practically simultaneously with the availability of the method of nuclear magnetic resonance and are known since about 60 years. The basic drawback of this type of magnetometers is the significant size of the magnetic coil systems (up to one meter), due to the requirements of low gradient of the bias fields and the significant size of the proton sensors. Figure 1(a) shows an example of such a system.

In recent years, the development of proton vector magnetometers achieved essential progress based on the application of the Overhauser effect providing stronger proton signal from smaller sensor size. This allowed to reduce dimensions of the bias coil systems and as a consequence, allowed to improve the sensitivity of measurements. The greatest success in design and introduction in observatory practice has been achieved by a joint project of GEM Systems Inc., Eötvös Lorand Geophysical Institute (ELGI), and Mingeo. The Fig. 1(b) shows the bias system (9 ring coils on a 30 cm sphere) and one of its co-authors L. Hegymegi.

Zhirov G. and Pack V. made a similar development in Kazakhstan and Russia in 1993 on the basis of the Braunbeck coil (magnetometer MK-2, size of magnetic coil system 28 cm) with the use of the Overhauser sensor OS-2 developed by the Quantum Magnetometry Laboratory of USTU. This system was successfully installed and tested during the 1994 Observatory Workshop in Dourbes (Fig. 1(c)).

1.1 Variometers

The Overhauser vector magnetometers are used for stable registration of the modulus and the direction variations of the Earth's magnetic field (declination D and inclination I). One of the basic problems is the stability of installation of the magnetic system on the pillar in the observatory or the support in field conditions, which can cause baseline drifts. To solve this task, taking into account the small size of the Overhauser vector systems, GEM Systems has applied a proven way of vertical suspension. The device is shown in the Fig. 2(a). The size of the spherical magnetic system is 20 cm, using 12 perpendicular rings (development of ELGI). The drift is claimed to be below 0.1 nT/°C and a long term stability of the geomagnetic component measurement less than 1 nT/year at sensitivity up to 0.01 nT is announced.

1.2 Absolute measurements

Presently, in almost all observatories, the measurement of the absolute values of the field vector orientation angles I and D are carried out by the "DIflux" instrument. The DIflux is used together with a separate proton magnetometer for measuring the full vector. A DIflux measurement protocol (DMP), eliminating all errors resulting from misalignment of the fluxgate magnetic axis and the telescope optical axis is used for obtaining absolute measurements of D and I (Lauridsen, 1985). The DMP also compensates most mechanical errors of the theodolite.

Since 1982, a theodolite borne vector proton magnetometer (see Fig. 2(b)), developed by Volker Auster, Magson GmbH Germany (Auster, 1984), is used for geomagnetic survey by the Geomagnetic Observatory Niemegk. This instrument tries to unite the advantages of the DIflux method and proton vector magnetometer. However in the DIflux instrument, the fluxgate is mounted on the telescope of the nonmagnetic theodolite whereas in the MAGSON in-

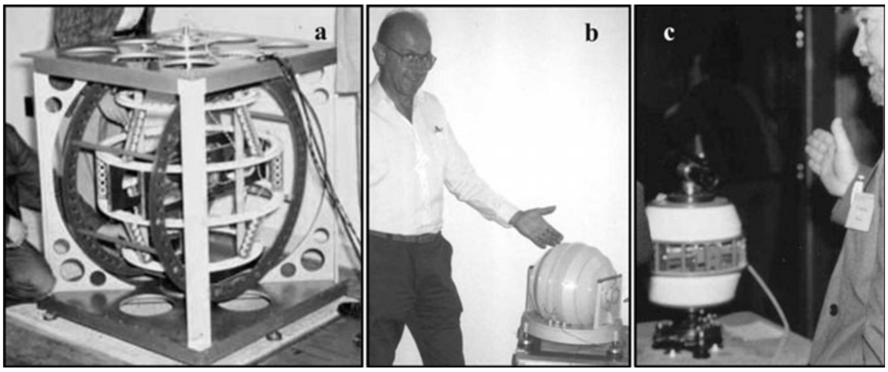

Fig. 1. Examples of the bias magnetic systems for proton and Overhauser dIdD magnetometers.

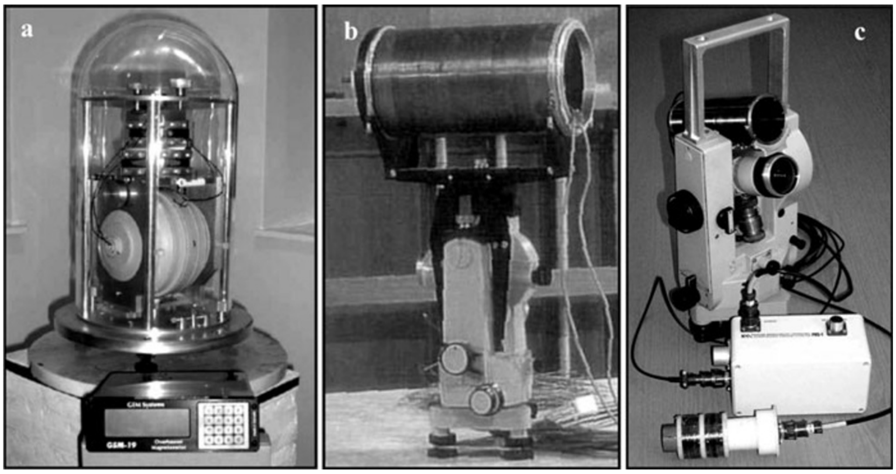

Fig. 2. Designs of the vector scalar magnetometers (a - suspended dIdD Overhauser GEM magnetometer, b - theodolite-borne proton MAGSON magnetometer, c - DIMOVER of QMLab. The Overhauser sensor is taken from the solenoid and is shown on the foreground).

strument, the Garret solenoid and proton sensor are not mounted on the telescope but on the alidade of the theodolite. The Overhauser sensor does hence not participate in the plunging around the theodolite horizontal axis in the measurement procedure. Thus the DMP cannot be fully realized and alignment errors remain which have to be corrected by a comparison measurement.

We analyzed the MAGSON design and discussed it with the designers of Russian theodolites. They explained that the prisms, which provide measurement of azimuth and vertical angles, are mounted directly in the telescope and that we can benefit from the special systems of self-compensation, in particular of the vertical angle index. So they encouraged us to mount our sensor (Overhauser + Garret coil) directly on the telescope to exactly reproduce the angular disposition and compensation that is actually used in the DIflux method. We would thus be able to exploit the full error correcting benefits of the DMP.

Addressing the problems stated in the previous paragraph, the Quantum Magnetometry Laboratory of USTU has succeeded in designing a bias magnetic system and Overhauser sensor small enough to be mounted directly on the telescope of a non-magnetic theodolite. The Fig. 2(c) gives a view on the prototype model. The development of this design has set the requirements for a number of theoretical and experimental tasks whose results are now presented.

1.3 The prototype DIMOVER sensor

The used Overhauser magnetometer needs power of about 2 Ws at sampling intervals of 1 to 6 s and sensitivities better than 0.1 nT. The working volume has the size $\varnothing 28 * 40$ mm whereas the Garret coil measures $\varnothing 55 * 150$ mm. We do not know the field homogeneity over the working volume precisely as experimentally it could not be measured. We estimated it theoretically and by precession signal decay. Computation gives 0.1% inhomogeneity at the edge of the solenoid but signal decay indicates a lower one. Our best optimization of the Garret coil gave a proton decay time of about 0.4 s, allowing proton precession measurements to be made with a noise level below 0.1 nT. For the absolute measurements of D and I, we do not expect the inhomogeneity to affect the accuracy, as the 4 symmetrical positions for each angle D or I (Lauridsen, 1985) will average out any effect, be it scalar or angular.

2. Method of Measurement Based on Switched Bias Field and Analysis of Errors

To measure the components of the geomagnetic field by a proton (scalar) magnetometer a number of methods are known. We investigate below the set-up based on the

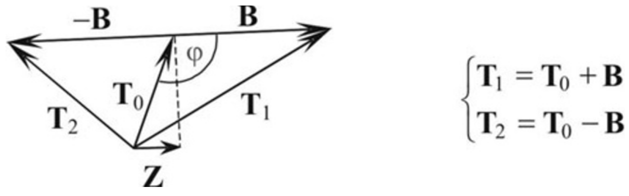

Fig. 3. Vector circuit for a switching method.

switching of bias magnetic fields (cycle $+J$, $-J$, $J = 0$) with the measurement of resulting total field (Serson, 1962). The vector circuit for the switching method (Fig. 3) and formula (1) for calculation of the field component along the bias field are shown:

$$Z = \frac{T_2^2 - T_1^2}{2\sqrt{2(T_2^2 + T_1^2 - T_0^2)}}. \tag{1}$$

It is a well-known formula, but, unfortunately, it gives practically no real information to choose the value and direction of the bias field. Nor does it give the effect of the selected parameters upon the resulting random and systematic measurements errors on Z.

2.1 Magnetic declination D measurement with DIMOVER

We present below the absolute measurement protocol and sensitivity analysis for the magnetic declination D measurement with a DIMOVER. The absolute measurement of the magnetic inclination I is similarly adapted from the DMP.

Other elements of the geomagnetic vector, such as the vertical component Z can also be measured, but we do not address this in this section.

2.1.1 Procedure In analogy with the DIflux DMP, we propose the following procedure for measuring D with the DIMOVER, in a geomagnetic field with modulus T_0 and Inclination I.

1. The DIMOVER theodolite is levelled so that its vertical rotation axis indeed coincides with the local Vertical.
2. The telescope is oriented precisely so that the optical axis is horizontal. Hence the Garret coil is also horizontal, save for the misalignment error, the so-called collimation error. This is completely described by 2 angles:
   a) Site error angle measuring the misalignment in the vertical plane.
   b) Azimuth error angle measuring it in the horizontal plane.
3. The theodolite alidade is rotated so as to align the telescope (and coil) in the approximate magnetic East/West direction, so that $\alpha \sim 90°$.
4. Now the Garret coil is energized with a current J so as to produce a field B towards West. Together with the geomagnetic field T_0 this will generate the field T_1 measured by the scalar magnetometer located inside the Garret coil.
5. Then the Garret coil is energized with a current J so as to produce a field B towards East. The scalar magnetometer measures now T_2.
6. By computing $\Delta T = T_2 - T_1$, the observer can determine if the coil is normal to the geomagnetic field vector, since $\Delta T = 0$ then (see below). If not, the observer will apply small changes to α with the slow motion screw of the theodolite to bring ΔT down to zero. Then the magnetic meridian trace is read on the theodolite horizontal circle. If the zero of the horizontal circle graduations has a known azimuth, the declination can be easily computed.
7. The same procedure is repeated 3 more times, with the positions in step 3 varied as the sensor is above or below the telescope, the latter pointing to the East or West. This gives a total of 4 positions for observing the magnetic meridian orientation.
8. The average of the 4 circle readings—corresponding to the 4 positions—are taken, eliminating the collimation errors (Lauridsen, 1985).

2.1.2 Analysis of the DIMOVER sensitivity Using the notations of Fig. 4, we compute the module of the vectors T_1 and T_2, with the known values of I, T_0 and B as we are varying α:

$$T_1 = \sqrt{B^2 \sin^2 \alpha + (T_0 \cos I - B \cos \alpha)^2 + T_0^2 \sin^2 I}, \tag{2}$$

$$T_2 = \sqrt{B^2 \sin^2 \alpha + (T_0 \cos I + B \cos \alpha)^2 + T_0^2 \sin^2 I}. \tag{3}$$

We are looking for the value of

$$\Delta T = T_2 - T_1, \tag{4}$$

which we can write as:

$$\Delta T = \frac{T_2^2 - T_1^2}{T_2 + T_1}. \tag{5}$$

Here we make an approximation for the case $\alpha \sim 90°$, which is the operating value:

$$T_2 + T_1 \cong 2\sqrt{T_0^2 + B^2}. \tag{6}$$

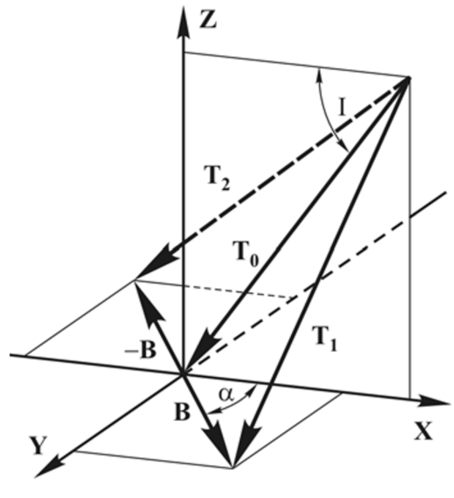

Fig. 4. Diagram showing the different vectors entering into the DIMOVER D measurement procedure. By rotating the theodolite alidade, i.e. varying α, B's are set orthogonal to T_0, which will realize $\Delta T = T_2 - T_1 = 0$.

Hence:

$$\Delta T \cong \frac{-2T_0 B \cos I \cos\alpha}{\sqrt{T_0^2 + B^2}}. \tag{7}$$

This equation shows the usefulness of ΔT as a zero indicator for setting the orthogonality of the Garret coil to the magnetic meridian. ΔT will be zero for $\alpha = 90°$ (save for he coil misalignment) and provide appropriately signed signals guiding the operator while seeking this zero.

The sensitivity for declination measurement is found by derivation with respect to α:

$$s = \frac{\delta(\Delta T)}{\delta\alpha} = \frac{2T_0 B \cos I \sin\alpha}{\sqrt{T_0^2 + B^2}} \times \frac{\pi}{180 \times 3600}, \tag{8}$$

where we have normalized the expression to get the sensitivity in nanoteslas per seconds of arc theodolite rotation. It is immediately apparent that there is a dependence of sensitivity on the magnetic Inclination and hence on latitude, the DIMOVER having maximum D sensitivity at the magnetic equator ($I = 0$) and gradually less sensitivity when nearing the magnetic poles. But then this is similar to the latitude dependency of the DIflux.

Concerning the dependency of the sensitivity on the value of B, which is an important adjustment parameter, we notice that

$$\lim_{B\to\infty} \frac{T_0 B}{\sqrt{T_0^2 + B^2}} = T_0, \tag{9}$$

meaning that the sensitivity cannot go higher than

$$s_{\max} = 2T_0 \cos I. \tag{10}$$

However B cannot be taken too high, as it will exacerbate the field homogeneity problems of the miniaturized Garret coil. A good deal of trial and error must be done to optimize the value of B but a valid starting value is $B = T_0/2$ which gives a sensitivity of:

$$s_{\text{start}} = 2T_0 \cos I/\sqrt{5}, \tag{11}$$

about half of the maximum one $s_{\max}$.

Is there a substantial change in ΔT when T_0 changes? I other words, is it necessary to measure T_0 during every cycle? Inspection of equation (7) shows that if T_0 changes, it will not affect the zeros of $\Delta T(\alpha)$. However the sensitivity s will be slightly affected by a change in T_0. This effect is given by the derivative:

$$\frac{\delta(s)}{\delta T_0} = \frac{2B^3 \cos I \sin\alpha}{\sqrt{(T_0^2 + B^2)^3}}. \tag{12}$$

Since the DIMOVER instrument is a zero seeking device, and changes in s do not affect the zero, there is not strictly a need for measuring T_0 at every cycle. This will allow speeding up the measurement.

Note that B and T_0 are symmetric in the formulas (7) and (8), so they can be interchanged for the sensitivity analysis.

2.1.3 Example of sensitivity computation for DIMOVER measuring the magnetic meridian

Let us compute an example with a geomagnetic field of $T_0 = 50000$ nT modulus and an inclination of $I = 65°$. We find the maximum sensitivity ($B \to \infty$):

$$s_{\max} = 0.20 \text{ nT}/''.$$

Let us assume that the field generated by the Garret coil is $B = 25000$ nT. We find:

$$s_{\text{start}} = 0.0916 \text{ nT}/'',$$

which is a sensitivity quite suitable since most modern proton magnetometers are able to measure 0.1 nT, including our Overhauser subjected to the Garret coil field.

This example shows that in the specified geomagnetic field, a 25000 nT B field will allow pinpointing the magnetic meridian with $1''$ accuracy provided the scalar magnetometer used in the DIMOVER has ~0.1 nT real sensitivity.

If T_0 is increased by 1% to 50500 nT, the sensitivity will become:

$$s_{\text{start}} = 0.0918 \text{ nT}/'',$$

which is a change of only about 0.2%. We can hence count on a stable and accurately known scale factor in DIMOVER, provided T_0, B and I are known with an accuracy of about 1%, which is generally true in an observatory.

2.1.4 Similarities and differences with the DIflux

From the above paragraphs, it is clear that the DIflux metrology applies to the DIMOVER. In particular we can average out the collimation azimuth and site errors (Lauridsen, 1985) by performing the usual plungings around the vertical and horizontal axes and taking the mean of the measurements.

However there is no sensor error as the Overhauser sensor has no residual magnetism like the fluxgate. Therefore there is one unknown less to eliminate, which makes the metrological procedure more robust and noise resistant. This is also an additional benefit for the DIMOVER when testing the magnetic hygiene of the whole device (no need to remove the sensor).

For the DIflux, the fluxgate output guides the operator to find an electronic null pinpointing the theodolite position with telescope normal to the geomagnetic vector. The electronic output operates without delay. For the DIMOVER however, the indicator ΔT value, computed from 2 successive T_1 and T_2 magnetometer readings, can be substantially delayed—depending on the speed of operation of the proton magnetometer. This will make the task of the observer more difficult if the delay needed to get ΔT exceeds ~1 s. Additionally the ΔT procedure may introduce errors if the field is drifting. We examine this in the next paragraph.

2.2 Error caused by the drift of the geomagnetic field

It was revealed by experiments with breadboard models of the Overhauser vector magnetometers, when fast changes of the geomagnetic field were simulated, that the switching method has a dynamic error. Variations of the measured component may exceed the real variations. The error grows with the increase of speed of variations. A physical explanation is obvious enough. The basic formula for calculating

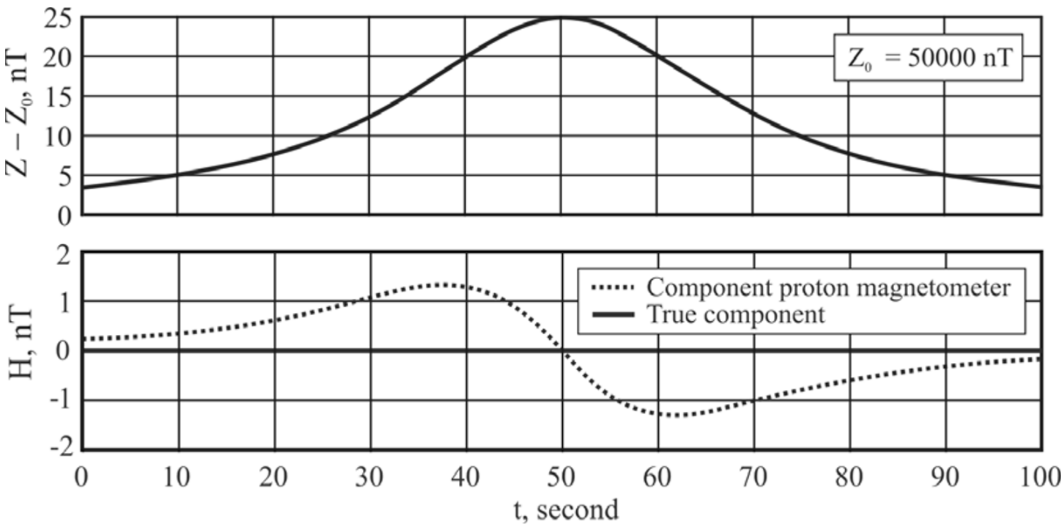

Fig. 5. Error caused by the drift of the geomagnetic field as result of dynamic cross effect of the proton vector magnetometers (The cycle at calculations is chosen 3 seconds).

the components makes the assumption of field stability. Estimations of this important kind of a dynamic error are given below.

To estimate the error caused by a field variation, the jump function model of a variation was simulated. Namely: at the first measurement the geomagnetic field is displaced by $-\Delta h$, in the second there is no displacement and in the third the field is displaced by Δh. A vector proton magnetometer will calculate the Z component of field according to the basic equation (1). The error is defined as the difference between the measured and calculated component without the drift Δh, that is $\Delta Z_1 = Z' - Z$:

$$\Delta Z_1 = \frac{T_2'^2 - T_1'^2}{2\sqrt{2(T_2'^2 + T_1'^2 - 2T_0'^2)}} - Z = \frac{1}{B^3}[T_0 \times B][B \times \Delta h] \leq \Delta h T_0 / B. \quad (13)$$

The analysis of (13) has shown that the drift error is the display of dynamic cross effect:

- There is an influence (error) at the presence of variations of perpendicular components.
- The error is proportional to speed of a variation to be exact is proportional to change of a field during a cycle of measurement components ($\sim$ the quantized time derivative of field).

Figure 5 shows an example of a computer calculation of the drift error. The top figure is a simulated Z variation. The bias magnetic system is perpendicular and the measurement of H-component is made along to bias field. The variation in H direction is absent. The bottom demonstrates this error.

Some discrepancy of variation measurements between the fluxgate and the proton vector magnetometers should hence be observed. It is obvious that the drift error can be excluded by improvement of the basic formula (1) or by processing measurements taking into account the speed of the components variation.

3. Breadboard Model of the PC-Based Vector POS-1 Magnetometer

A PC-based vector POS-1 magnetometer was created on the initial stage of our researches to check experimentally some theoretical estimations stated above. Braunbeck coils were used as magnetic bias system (∅28 cm). The experimental research has shown the validity of the formulas presented above and of the drift error caused by fast variations in particular. We refer the readers to www.magnetometer.ru where a complete report is available and where new results on DIMOVER will be presented.

4. Theodolite-Borne Vector Overhauser Magnetometer

The use of the small Overhauser sensor and optimized Garret solenoid gave the physical basis for the installation of the vector sensor directly on the theodolite telescope (Fig. 2(c)). The usual 1″ basic accuracy theodolite 3T2KP of the Ural Optical & Mechanical Plant (Ekaterinburg, Russia) was demagnetized. It was then certificated as a DIflux theodolite at Geophysical observatory “Klyuchi” (Novosibirsk, Russia). The electronics of the standard POS-1 Overhauser magnetometer was used and an additional block for the current supply of the magnetic system was added. We expect to be able to present real world measurements soon.

It is supposed that apart from observatory work the proposed device will find applications for geological surveys of kimberlite in complex magnetic fields connected with trap formations. There is a Z-magnetometer variant, without a theodolite, which is based on a vertically gravitationally positioned solenoid so as to speed up the prospecting.

We postulate that the basic application of the DIMOVER (device or its design) can be useful in magnetic observatories and field surveys because:

- co-location of the measurement of D, I and T that will allow to exclude the dT pillar correction,
- only one device must be transported and powered which is an important advantage for field operations,

- DIMOVER is a fully nonmagnetic device with no sensor magnetisation error.

5. Conclusion

We hope the brief review of the proton vector magnetometers is interesting and useful from the point of view of development of these devices.

We presented an error analysis and basic parameter optimization of the method of measuring a component by the absolute magnetometer. In particular the drift error caused by dynamic cross effect is estimated.

For absolute D and I angular measurements, the same sensitivity and accuracy as the best DIflux is expected ($1''$).

Unfortunately, on the one hand, the presented theodolite-borne vector Overhauser magnetometer has a number of shortcomings now; namely its low speed (6–9 seconds), a delayed null indicator and an error dependent upon the time derivative of the field. On the other hand we hope that in this case a number of problems on the long-term stability of the measurements and the automation of the base line control can be innovatively resolved.

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